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Incandescent radiation sources are widely used as mid-infrared emitters owing to the lack of alternative for compact and low cost sources. A drawback of miniature hot systems such as membranes is their low efficiency, e.g., for battery powered systems. For targeted narrow-band applications such as gas spectroscopy, the efficiency is even lower. In this paper, we introduce design rules valid for very generic membranes demonstrating that their energy efficiency for use as incandescent infrared sources can be increased by two orders of magnitude.
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Current low cost and compact size (0.1–10 mm^2) infrared (IR) sources are light-emitting diodes (LEDs) and hot membranes which exploit blackbody radiation $\varphi_{\rm rad}(\lambda, T)$ at a temperature T. They are needed for gas detection, for instance, to detect CO_2 using the infrared narrow band $[\lambda_1, \lambda_2] \equiv [4.16\,\mu m, 4.36\,\mu m]$. Unfortunately, both kinds of sources have poor efficiency which is a drawback to obtain autonomous devices. Indeed, due to the λ^{-3} scaling of the spontaneous emission rate of excited carriers in semiconductors, mid-IR LEDs have a drastically lower efficiency than visible LEDs, typically 10^{-4}. On the other hand, hot membranes are plagued both by their wideband emission following Planck's law (while targeting a narrow band) and by their thermal leaks.[1–4] For a quantitative analysis, their wall-plug spectral efficiency is defined as $\eta_{\rm wp} = \int_{\lambda_1}^{\lambda_2} \varphi_{\rm rad}(\lambda, T) d\lambda / P_{in}$, the flux in the targeted band (which is in the following of the paper [4.16 μm, 4.36 μm]) divided by the input power P_{in}. First, even when operating close to the optimum Wien wavelength, the flux radiated at $\lambda = 4.26 \pm 0.1\,\mu$m is about 3% of the total radiative flux. Moreover, competition between IR radiation $\varphi_{\rm rad}$ and thermal leaks at $T \sim 1000$ K is much worse than in the visible, due to the T^4 scaling of $\varphi_{\rm rad}(T)$ given by Stefan's law. To reduce these thermal leaks, recent work uses tiny wires to hold the membrane. Yet, it was shown that such membrane sources for CO_2 sensing have an efficiency $\eta_{\rm wp} \simeq 0.05\%$.[1]

In this Letter, we describe mm-size membrane emitters, in the MEMS (Micro-Electro Mechanical Systems) context, that perform much better by using the so-called radiative fin approach, together with spectrally optimized emitters around $\lambda \simeq 4.2 \pm 0.1\,\mu$m, increasing the efficiency by two orders of magnitude $\eta_{\rm wp} \simeq 6.5\,\%$. Our strategy makes use of the radiative fin concept, in other words the concepts governing how a thin slab (or a fin), heated on an edge, cools down radiatively all the way towards its free ends. The result surprisingly departs from the "even tinier wire" belief invoked above. Besides, the emitter is also improved, in comparison to the blackbody, by placing the membrane at the antinode of a quarter wavelength above a reflective surface, the so-called Salisbury screen (see, e.g., the review by Watts *et al.*[5] for this and for further progress).

Let us start by a short comparison with the current art of Fig. 1(a), typical of MEMS: a membrane held by two thin arms to get stiffness and mitigate heat leakage.[1–3] For such devices, favoring IR emission by rising the temperature hits a limit: above $T_F = 1000$ K, their lifetimes are jeopardized.[1] At variance with Fig. 1(a), our design, Figs. 1(b) and 1(c), has virtually no arms, the membrane having only apertures (not shown) for technological needs. At first sight, it amounts to extend the angle θ defining the arms of Fig. 1(a). However, if radii are conserved, thermal leaks may remain prohibitive. The radial scaling of thermal leaks is thus the crux of our design, hinging on the radiative fin physics and representing a large departure from former implementations[1–3] in which the heating power distribution in the device was kept uniform.

We will now discuss all kinds of heat channels in more detail as follows: (i) How convection suppression results from the device encapsulation in vacuum, e.g., with a transparent silicon window. (ii) How a well designed spectral emissivity reduces unwanted IR emission. (iii) How heat flow by conduction *at the membrane-substrate junction* can be reduced, adapting the so-called radiative fin approach.

For the convection first, once a membrane is encapsulated, losses through the air can be virtually suppressed if a vacuum better than 1 Pa (10^{-5} bar) can be achieved. Specifically, both leakages from the upper face and through the tiny gap between membrane and substrate become negligible compared to the IR flux. This is what we assume here.

The second point is the spectral design, using a nanophotonic version of the Salisbury screen.[5–7] At point $\mathbf{r}$ of the membrane, instead of the net radiative flux $\varphi_{rad}(\mathbf{r}) = \sigma[T(\mathbf{r})^4 - T_a^4]$ of an ideal blackbody against a blackbody background at T_a, we have a wavelength-dependent emissivity $\epsilon(\lambda)$ requiring integration

$$\varphi_{rad}(\mathbf{r}) = \int_0^\infty d\lambda\, \pi\, \epsilon(\lambda)[I_\lambda(T_1(\mathbf{r})) - I_\lambda(T_a)], \qquad (1)$$

where $I_\lambda(T)$ is the spectral radiance of the modified membrane. Since, by Kirchhoff's theorem $\epsilon(\lambda) = \alpha(\lambda)$, the

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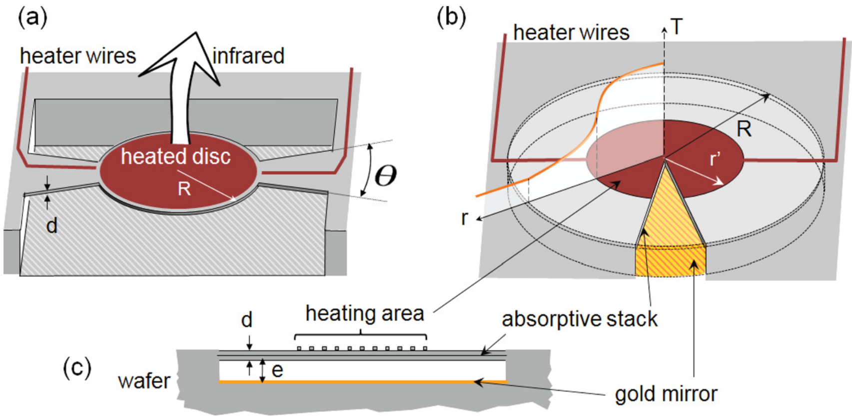

FIG. 1. Schematic view of thin (thickness $d = 350$ nm) circular incandescent membranes for infrared detection. (a) State-of-the-art layout of a free-standing membrane of radius $R = 75\,\mu$m, held by two arms spanning an azimuthal range θ, and entirely heated. (b), (c) Proposed layout: the edge of the membrane of radius R (few millimeters) is in direct contact with the wafer substrate within technological allowances. It lies above a gold mirror at a reduced distance e, as seen in the cut of (c). A radial thermal profile is also sketched in (b).

emissivity is provided by an electromagnetic calculation of the normalized absorption $\alpha(\lambda)$ of a plane wave hitting the membrane. It is well known[6–8] that a membrane above a mirror has a spectrally structured absorptivity due to interferences. Here, using MEMS compatible materials, we first sandwich a very thin layer of platinum between two thicker layers of non-absorptive silicon nitride, SiN, see Fig. 2, to get a critical value for the single-pass absorption (in the language of the microwave community, the membrane impedance due to Pt sheet conductivity has to match that of vacuum 377 $\Omega_\square$). With a gold mirror located on the substrate at a distance $\lambda/4 \simeq 1.05\,\mu$m beneath the platinum and for a critical platinum thickness of 5 nm, the system absorption at $\lambda_0 = 4.26\,\mu$m can be boosted to nearly 100% even though the single pass absorption in the membrane is much lower. The resulting thermal emission at $T = 1000$ K is shown in Fig. 2 with a blackbody reference. Note that this emissivity is that of a very simple and rather feasible system, with several better quasimonochromatic emitters reported,[9–14] so it is a conservative approach in terms of efficiency enhancement. There is room, for instance, to mitigate an expected efficiency drop for a larger gap e by a more engineered membrane inspired by the numerous metamaterials studies,[5] e.g., with periodic features adapted to cancel the short or long wavelength tails around the desired peak.

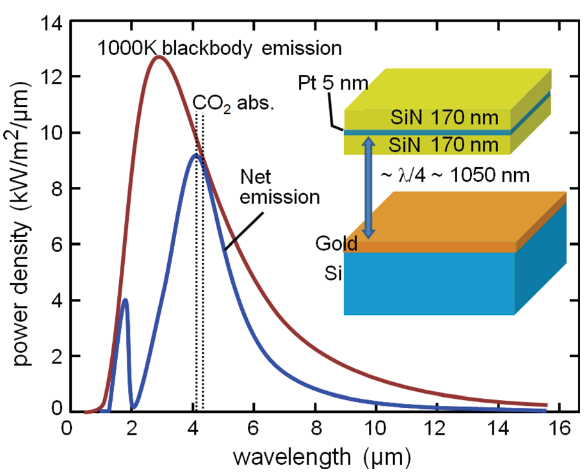

FIG. 2. A layered structure optimizing thermal emission at $4.26\,\mu$m. As shown in the inset, a 5 nm platinum layer is sandwiched between two 170 nm-thick SiN layers and a gold mirror is positioned below at $e = 743$ nm. The dark red curve shows the reference blackbody spectrum emission at $T_F = 1000$ K, the blue one the net emission for the stack for the same temperature.

The third point, conduction, can now be examined in a comparative manner. To implement a highly efficient incandescent system, the main idea that will lead us to the radiative fin picture below is to ensure that heat can escape the membrane through radiation faster than through conduction. We first tackle qualitatively this issue from the time point of view and next from the spatial point of view. So, what are the relevant characteristic times? We know that heat diffuses across the thin membrane in a time $\tau_d = \rho\, c_p d^2/k$, where ρ, c_p, and k are the density, specific heat, and thermal conductivity of the membrane, respectively. For SiN, the majority membrane constituent, $\rho\, c_p/k \simeq 7.8\,\mathrm{s\,cm^{-2}}$. For a thickness $d = 350$ nm, $\tau_d \sim 10$ ns only, so the membrane, heated from top (Fig. 1(c)), is isothermal vertically, a key approximation of the radiative fin approach. A much longer time governs heat diffusion from the disk center to its edge, $\tau_R = \rho\, c_p R^2/k$ which is on the order of 1 ms for a radius $R = 100\,\mu$m. We compare this time scale with a cooling time τ_{conv} defined by describing the whole heat transfer between the disk of area πR^2 and its environment by a radiative loss that is locally linearized vs. temperature, giving a convection-like flux $\varphi_{\rm rad} = h_{\rm rad}(T(r) - T_a)$, valid for $(T(r) - T_a) \ll T_a$, and an $\exp(-t/\tau_{conv})$ cooling law. Assuming *a priori* that the cooling time τ_{conv} is larger than the diffusion time so that the disk is isothermal, we find $\tau_{conv} = \rho\, c_p\, d/h_{\rm rad}$. The ratio of the conduction time τ_R to τ_{conv} is then

$$\alpha = \frac{\tau_R}{\tau_{conv}} = R^2 \frac{h_{\rm rad}}{k\, d}. \qquad (2)$$

If $\alpha \ll 1$, radial heat transfer is quick, the disk tends to be radially isothermal. Conversely, if $\alpha \gg 1$, it means that convection-like cooling (whatever its true nature) is faster than the sole in-plane conduction towards the membrane edge. This is exactly the regime that we are searching as radiative losses are beneficial whereas conduction through the membrane leads to conduction losses. It follows that we are interested in a large value of the membrane radius.

In a complementary view, under such conditions, it becomes efficient to increase the θ angle of Fig. 1(a) because arms are more cooled radiatively than they are by conduction. This is the less intuitive part of the story, as, at first sight, increasing the arms subtended angle only increases the conduction losses. However, a longer thermal path to the edge for large R can more than counter this trend. So the time study hints at large disks, but more is needed about the spatial length scale. We get a simple insight by borrowing from the radiative fin approximation known in textbooks.[15] Using still $\varphi_{\rm rad} = h_{\rm rad}(T(r) - T_a)$, an equation with a single coefficient appears from the thermal balance vs. radius r

$$\nabla_r^2 T(\mathbf{r}) = m^2(T(\mathbf{r}) - T_a). \tag{3}$$

This coefficient $m = \sqrt{h_{rad}/(k\,d)}$ is the inverse of a length scale $1/m$ over which $\frac{\partial T}{\partial r}$ decays to small values, causing the conduction flux to vanish as well.[15] Thus it is a target length scale to reach the energy-efficient use of the unheated ring $r' < \mathbf{r} < R$ as a radiative fin [see Fig. 1(b)], with vanishing conduction losses at its edge, which can be written in dimensionless form $mR \gg 1$ which is identical to $\alpha \gg 1$.

We now shift gear to a full-fledged account of the radial thermal profile. The energy conservation for the membrane in the fin approximation can be cast in the form

$$k\nabla_r^2 T(\mathbf{r}) - \frac{\varphi_{rad}(\mathbf{r})}{d} + P(\mathbf{r}) = 0, \tag{4}$$

where $P(\mathbf{r})$ is the heat source density, nonzero if $|\mathbf{r}| \leq r'$ (inset of Fig. 3) and where $\varphi_{rad}(\mathbf{r})$ is calculated exactly as in Eq. (1), rather than being linearized. The two boundary conditions are $-k\frac{\partial T(0)}{\partial r} = 0$ and $T(R) = T_a$. The substrate at radius R behaves as a thermostat at T_a that absorbs all the conductive heat flux, $-k\frac{\partial T(R)}{\partial r}$, transferred to it. It is obvious that for the targeted center temperatures, $\sim$1000 K, the linearization of $\varphi_{\rm rad}$ is grossly invalid across the whole membrane. Still, the orders of magnitude induced from it are guiding us. Thus, we solved Eq. (4) for R varying from 75 μm to as much as 5 mm, while we let $0 \leq r' \leq R$. As for the design inputs, we retain here the $d = 350$ nm thickness. We believe such an option to be feasible in a vacuum setting, and with proper stress management to remain in tensile condition when partly heated. If a compromise with the relatively close gold mirror had to be done, let us remind that this emissivity was not strongly optimized, leaving room for technological compromises. Also, note that the fin approximation validity requires the fin's Biot number to be small:[15] $(h_{rad}/(k\,m)) \ll 1$ and this is always true when d is a few hundreds nanometers large as m is large enough. The useful emitting area shall also be somewhat larger than the heated area, but we will see that it is not much so, keeping an effective emitted power per unit area close to the ideal one.

After solving Eq. (4) we can study the efficiency of power conversion into IR flux as a function of r'/R as seen in Figure 3 for R = 5 mm. We find the optimal sub-disc radius to be $r'/R = 0.5$ for any large enough R.

Such critical power localization arises from a trade-off between two competing methods to increase the rate of thermal emission. (i) Having the largest surface at the maximum temperature T_F since too small surfaces suffer adversely from the radiative fin heat spread; (ii) minimizing losses by rendering the temperature difference between the edges and the substrate as small as possible (i.e., $\frac{\partial T(R)}{\partial r} \approx 0$).

This is the most efficient strategy to radiate the power heating the membrane, as virtually all of the heat is radiated away in the ring region between the heated part and the fixed edges. This can be seen in Fig. 4 where we have plotted the optimum temperature distribution for this configuration. The membrane is heated in the region that goes from the center to $r' = R/2$ and this is the hot part responsible for most of the emission. At the same time in the region that goes from $r' = R/2$ to R we can observe a quite sudden cooling of the system, hence our note that the emitter retains a high average radiance if typically a disc (pupil) of radius $r_{pupil} \geq R/2$ is coupled to the optical system line.

Finally, to illustrate the dependence of the efficiency of thermal emission, $\eta_{\rm wp}$, on the membrane radius R, we vary R from 500 μm to 5 mm and localize the heat supply within $r \leq r' = R/2$, but adjust it to keep the center of the membrane at T_F. By numerically solving the above heat equation, we calculate the amount of power converted into IR flux, and represent it in Fig. 5 as a function of R. The conversion efficiency from power to IR approaches 1 for $R \sim 5$ mm.

At the same pace, the efficiency $\eta_{\rm wp}$ for the quasi-monochromatic interval illustrated in the plot of Fig. 2 is calculated integrating the thermal radiation filtered by the spectral emissivity in Fig. 2 in the range [4.16 μm, 4.36 μm].

It is found to be proportional by a factor of 0.065 to the total integrated thermal flux while we remind that a "lossless" blackbody with the same temperature profile $T(\mathbf{r})$

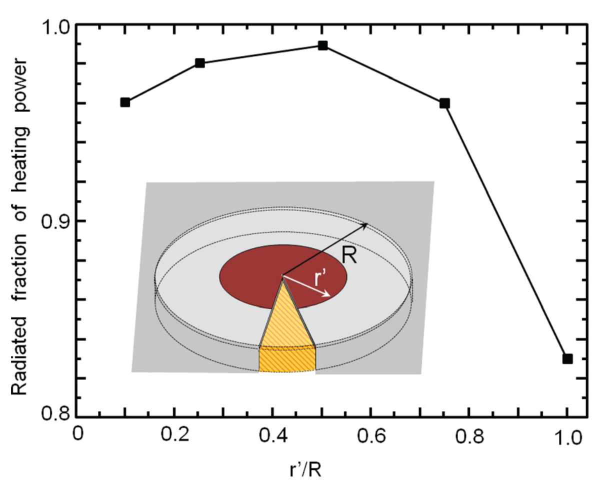

FIG. 3. The encapsulated membrane ($R = 5$ mm, $d = 350$ nm) is partially heated in a disk of radius r', as shown in the inset. Black squares show the fraction of heating power that escapes by thermal radiation as a function of r'/R. The line is a guide to the eye.

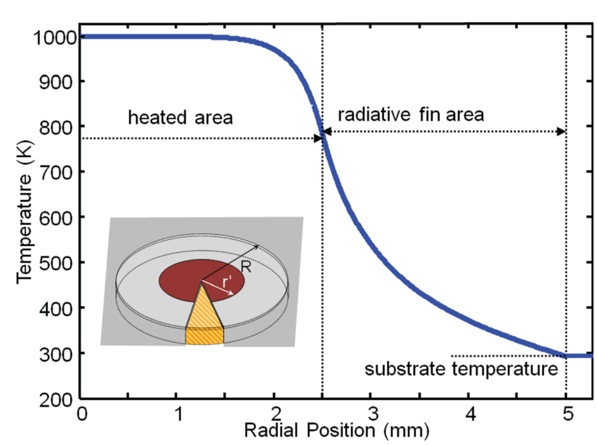

FIG. 4. Temperature distribution $T(\mathbf{r})$ for an encapsulated membrane ($R = 5$ mm $d = 350$ nm) when the power is concentrated in a radius $r' = 0.5\,R$.

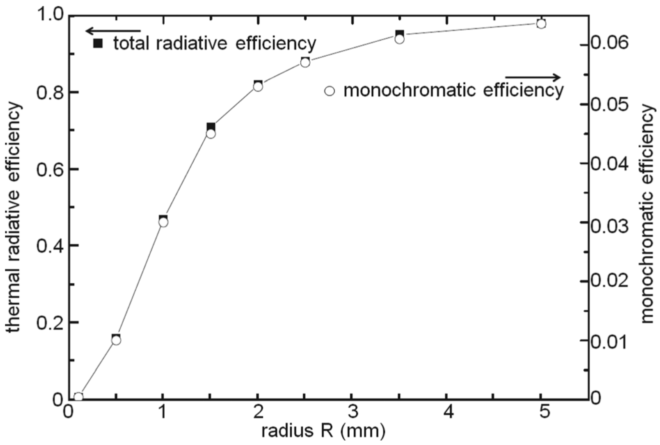

FIG. 5. Total (solid squares) and quasi-monochromatic (open circle) power conversion efficiencies as a function of membrane radius. For every R, input power is injected only within a radius $r' = 0.5\,R$ and is adjusted to bring the membrane center at 1000 K. The emissivity is that represented in Fig. 2. The line connecting the data is a guide for the eye.

yields a factor 0.035. The radiative efficiency 0.065 is essentially limited by the emissivity design. Much better performances can be obtained using quasi-monochromatic emitters.

In summary, we have shown theoretically that virtually all heating power can be converted into thermal radiation provided that some design rules are used. The hot membrane needs to be encapsulated in vacuum. Most importantly, the hot membrane should not be heated uniformly. Instead, the distance between the contacts and the hot central region should be larger than a typical decay length, causing the unheated part to act as a radiative fin and not a heat loss channel. This analysis raises the prospect of highly efficient incandescent sources for mid IR applications.

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